CHARACTERISATION OF STRESS CONCENTRATION FEATURES IN THE α+ β TITANIUM ALLOYS

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ABSTRACT: The paper explores the impact of texture in the titanium alloy Ti-6-4 on the fatigue response of plain and notched test-pieces. In particular it examines the behaviour of specimens orientated parallel (0 degrees) and perpendicular (90 degrees) to the rolling direction in uni-directionally rolled plate. The measurements clearly demonstrate the importance of basal plane orientation and available basal and prismatic slip systems in determining the observed fatigue lives. For this publication, notch effects are related to a round cylindrical geometry (RCN) with K_t = 1.4. Differences between strain control plain specimens and notches are noted. These are explained through the application of critical strain lifing methods such as Coffin-Manson and Walker. Differences induced by high R values are highlighted.

Keywords: Texture, titanium, notches, prediction

RESUMO: Este artigo explora o impacto da textura da liga Ti-6-4 no comportamento à fadiga de provetes lisos e entalhados. Em particular, é examinado o comportamento de provetes com orientação paralela (0^o) e perpendicular (90º) à direcção de laminagem de material laminado unidireccional. As medições demonstram claramente a importância da orientação do plano basal e sistemas de escorregamento disponíveis na vida à fadiga. Para este artigo, efeitos de entalhe foram estudados com uma geometria cilíndrica (RCN) com K_t = 1.4. Diferenças entre provetes entalhados e não entalhados testados com controlo de deformação são registadas e explicadas pela aplicação de métodos de previsão de vida baseados na deformação, como Coffin-Manson e Walker. As diferenças resultantes de valores elevados de R são sublinhadas.

Palavras chave: textura, titânio, entalhes, previsão

1. INTRODUCTION

Titanium alloys have been the 'work-house' materials for compressors in gas turbine engines for more than fifty years. Throughout that period there have been considerable advances in these alloys through alloy development, working processes and heat treatments.

Unfortunately, the incremental advances in properties we have come to expect are increasingly difficult to attain. Are we at the 'end of the line' for conventional titanium? Fortunately, the answer is no because of a property that we have previously sought to limit. This is texture, which in titanium alloys can be significant due to their inherent HCP crystallography. The problems with texture are its control through processing and then designing effectively with the resultant anisotropic properties.

The research on which this paper is based focused both on processing of Ti-6Al-4V to produce texture and the assessment of such textures in relation to mechanical properties [1-5]. Plane strain compression experiments demonstrated the dependence of texture on applied parameters such as temperature, strain rate and strain level. Mechanical characterizations focused on rolled plate and explored the behaviour in the rolling and transverse directions. Particular attention was given to LCF, HCF, notches and fatigue thresholds. Clear patterns of behaviour were defined with important interactions occurring between failure mechanisms, cyclic stress redistribution, cyclic stress-strain relationships and test piece orientation. This paper focuses specifically on the strain control fatigue response of plain test specimens and load control fatigue of notch specimens. Several notch geometries were evaluated but attention here is focused on a round cylindrical geometry (RCN) with K_t = 1.4. The main objective of this presentation is to demonstrate notch fatigue predictions from plain specimen data highlighting regimes in which the approach breaks down. To this end, test data over a range of R values are presented. A strong correlation of measured response with basal plane orientation and the availability of slip systems is demonstrated.

2. MATERIAL

The research programme focused on the α+β titanium alloy, TIMETAL 6-4. The alloy was supplied as unidirectionally rolled plate, with a plate thickness of 14mm.

Following processing the microstructure consisted of nearly equiaxed grains with a primary α volume fraction of approximately 80%. There was slight elongation of the grains in the final rolling direction.

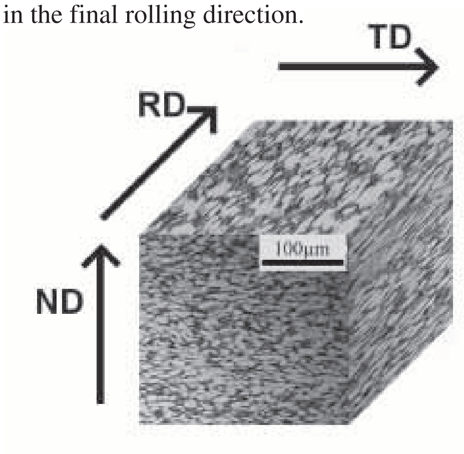

Fig. 1(a). Microstructure of Ti6-4

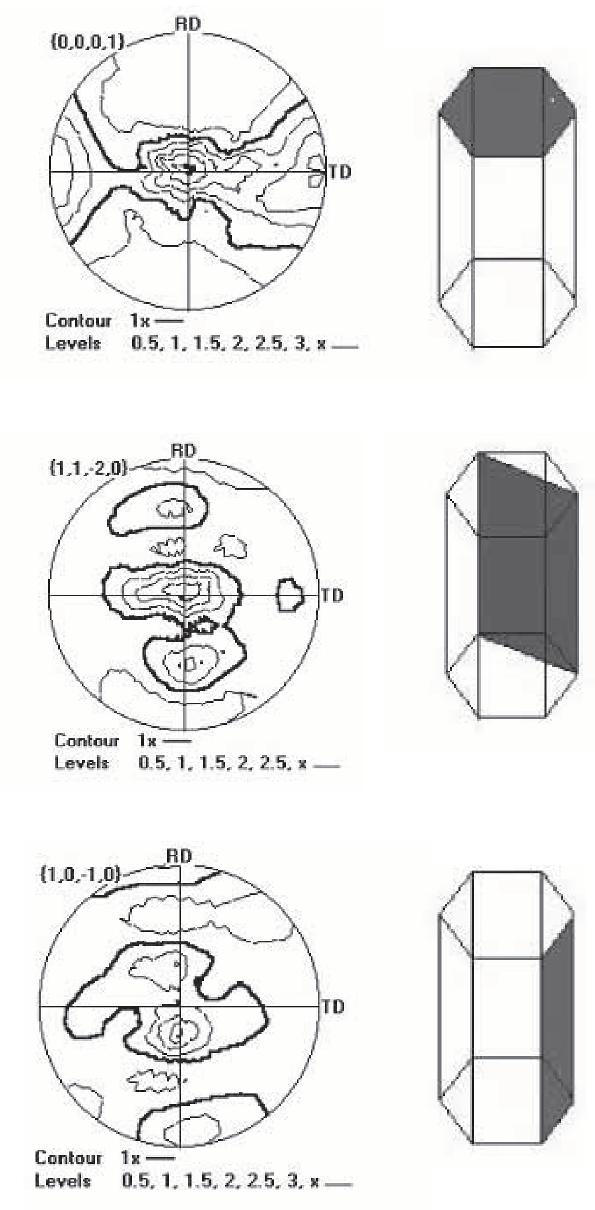

Fig. 1(b). Basal and prismatic faces

The average grain size was of the order of 15µm, Figure 1 (a). The crystallographic texture following processing is shown in Figure 1(b). The texture is completely described by the three orthogonal pole figures $(000\bar{1})$ $(11\bar{2}0)$ $(10\bar{1}0)$ .The material shows a classic basal/transverse texture of x3 random magnitude. This is not a strong texture but because of the high primary alpha content, significant anisotropy is observed [2].

3. EXPERIMENTAL METHOD

Strain control testing under tension was performed at room temperature using plain cylindrical specimens of 6mm diameter in accordance with BS7270[6] The test was controlled by an MTS extensometer with a gauge length of 10mm, and hysteresis loops were recorded using an in-house data logging system. Testing was conducted on specimens aligned at 0° (RD) and 90° (TD) to rolling direction. R ratios of -1 and 0 were employed, along with a trapezoidal 1-1-1-1 waveform.

Notch tests were undertaken under load control, at R ratios of -1 and 0, R=0.8 and a 1-1-1-1 trapezoidal waveform. The round cylindrical notch (K_t=1.4) specimen is shown in Figure 2.

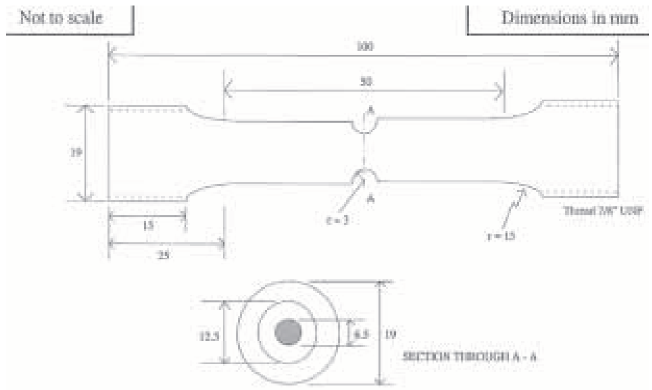

Fig. 2. The RCN test specimen

4. RESULTS

<u>Data Generation</u>

Strain control data are shown in Figure 3. There is good correlation at R=-1 but a marked difference in lives for the two orientations under R=0 conditions. The reason for this difference is stress relaxation during the early hysterises loops. In essence the 90° specimens relax to a higher stabilised stress. Further discussion of this phenomenon can be found in previous work[2]. The impact of relaxations is confirmed by Figure 4, which shows the same strain control results, with additional HCF load control data at R = 0, plotted on a stabilised stress basis. Clearly, the 0° and 90° data for each R value now superimpose. However, although the R=0 and -1 results merge at shorter lives (<10^5 cycles), at larger lives there are two distinct trends with the R=-1 data 'running out' to a higher stabilised strain range.

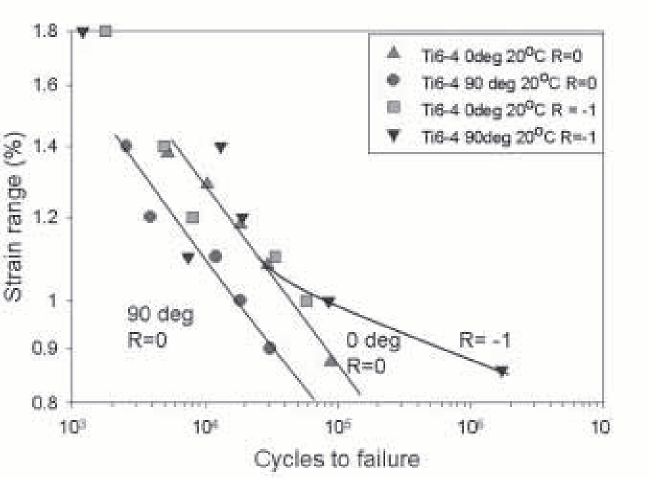

Fig. 3. Strain control results

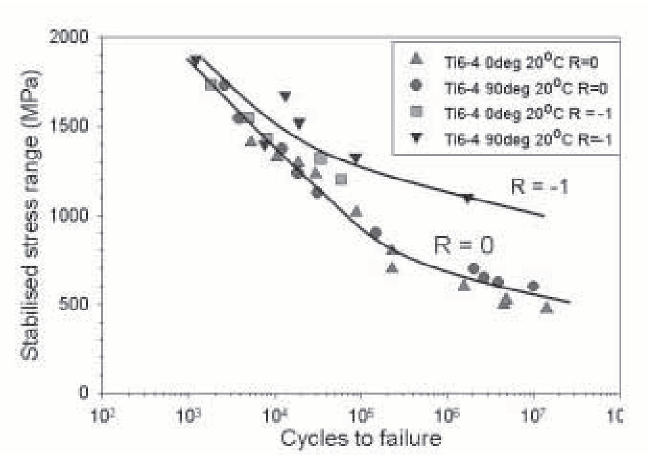

Fig. 4. Stabilised stress range

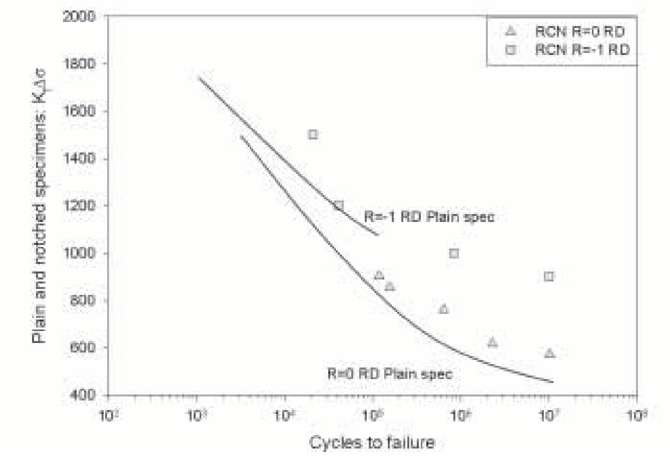

Fig. 5. RCN fatigue behaviour

The notch (RCN) tests at R = 0 and R = -1 are reported in figure 5 for both orientations. Data obtained at R=0.8 are presented later.

The RCN results show the same trends as the plain specimens when plotted on a peak elastic stress range basis. This is emphasised by the super-position of best fit lines from figure 4 on to figure 5. However, correlations of plain and notch behaviour using peak elastic stress ranges are limited in their regimes of applicability. It is generally more effective to use critical strain methods for predicting notch lives from un-notched data. To this end the Coffin-Manson (CM) and Walker critical strain approaches were evaluated.

<u>The Coffin-Manson method</u>

The Coffin-Manson approach [7, 8] partitions the applied strain range at R = -1 into its elastic and plastic components, i.e.

$$\Delta\varepsilon_{Tot} = C_e N_f^{\alpha 2} + C_p N_f^{\alpha 1} \qquad (1)$$

In the case of the 0 degree data these constants were determined to be

C_e = 0.031827 (Elastic constant)
C_p = 0.211 (Plastic constant)
α1 = -0.5986 (Plastic exponent)
α2 = -0.1053 (Elastic exponent)

Application of equation 1 in the prediction of notch behaviour requires the strain range at the notch root to be determined. Figure 6 considers the loading behaviour of an R = 0 notch. The equivalent elastic peak stress on loading is shown by point A on the graph. According to Neuber[9], material redistributes stress and strain at the notch root according to the relationship

Stress x Strain = constant (2)

This is seen as the hyperbolic curve AB. During the unloading phase the material moves elastically to the point C, which is in compression.

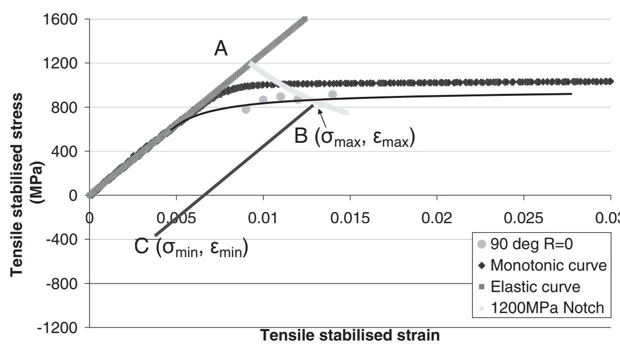

Fig. 6. Neuber calculation of notch stress/strain conditions

For R = -1 notches, the situation was simpler. The applied peak elastic stresses are approximately equal to or lower than the yield stress of the material, so purely elastic behaviour can be assumed.

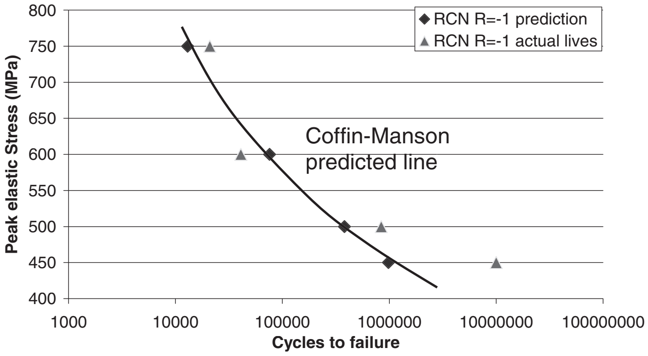

Fig. 7. Notch Predictions at R = -1

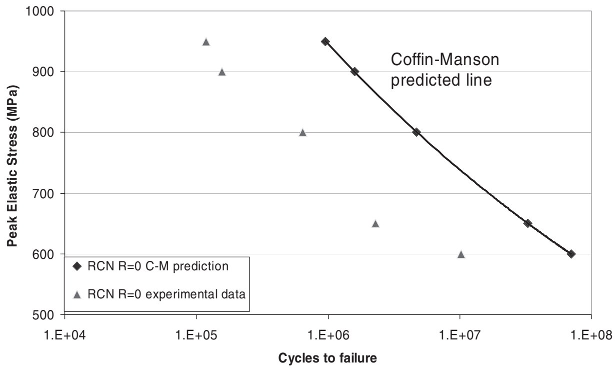

Fig. 8. Notch predictions at R = 0

Based on these calculations, the predictions made by the CM approach for the RCN in the 0 degree material under R = -1 loading conditions are shown in Figure 7. The calculated values accurately predict the measured lives. However the method was not as accurate for the 90° specimens in which significant over predictions of life are evident. The predictions of the 0 degree material were less effective for R = 0 loading conditions, figure 8. This is because even though the notch root moves into compression on unloading the mean stress and strains are positive so that the CM equation, which is based on fully reversed loading, becomes less effective.

The Walker strain method

The Walker strain relationship is an empirical method that allows for mean stress and strain influences [10]. The approach involves correlating strain control data at different R ratios using the expression

$$\Delta\varepsilon_w = \frac{\sigma_{max}}{E}\left(\frac{\Delta\varepsilon E}{\sigma_{max}}\right)^m \qquad (3)$$

where; $\Delta\varepsilon_w$ = Walker strain
σ_{max} = maximum stabilised stress
E = Modulus
$\Delta\varepsilon$ = strain range
m = Walker exponent

In the current work, strain control data have been produced for lives up to 10^6 cycles, at both R = 0 and R = -1. HCF data have also having been obtained at R=0. To apply the Walker strain correlation, it is first necessary to find an m value that gives the best super-position of data at different R values.

For the 0 degree orientation data, the m value in equation 3 was optimised at 0.5. However, for the 90 degree specimens it was significantly different at m=0.3. This is probably due to the different relaxation behaviour of the orientations.

Using the appropriate m value, the 0 degree orientation obeys the relationship

$$\Delta\varepsilon_W = 0.0286 N_f^{-0.1225} \qquad (4)$$

while for the 90 degree orientation it has the form

$$\Delta\varepsilon_W = 0.0161 N_f^{-0.0756} \qquad (5)$$

This expression describes the plain specimen response. For the prediction of notch behaviour it is necessary to determine the Walker strain at the notch root. The strain is given by the relationship

$$\Delta\varepsilon_W = \varepsilon_{max}(1-R)^m \qquad (6)$$

Equation 6 assumes elastic behaviour at the stabilised loading conditions, as illustrated by point A in Figure 6.

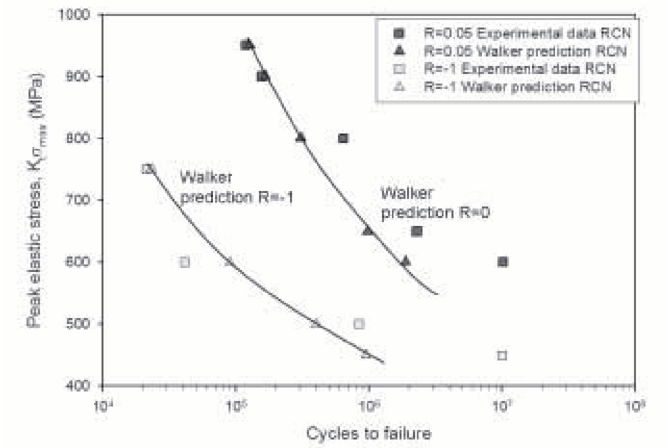

Fig. 9. Walker predictions for 0° RCN

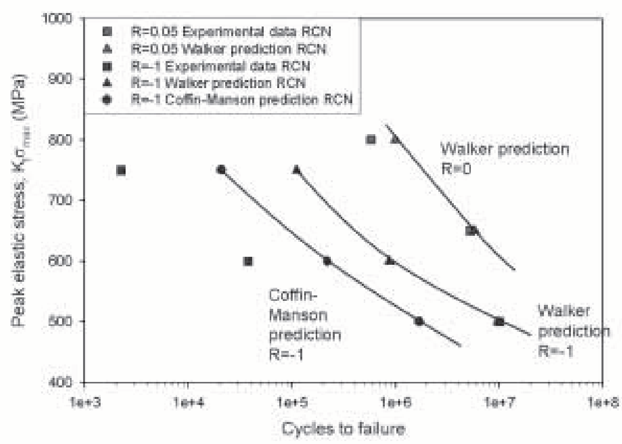

Fig. 10. Walker and CM predictions for 90° RCN

The resultant predictions are shown in Figures 9 and 10. The Walker equation for the 0° orientation predicts both R=0 and -1 behaviour accurately. In the 90° orientation the R = 0 data is better predicted but only at high lives.
A major limitation of the Walker approach is evident at high R values. This is clear from figure 11 which contains measured data for both 0° (RD) and 90° (TD) orientations at R=0.8. The Walker predictions clearly overestimate the measurements for both orientations. This is attributed below to the occurrence of additional modes of failure.

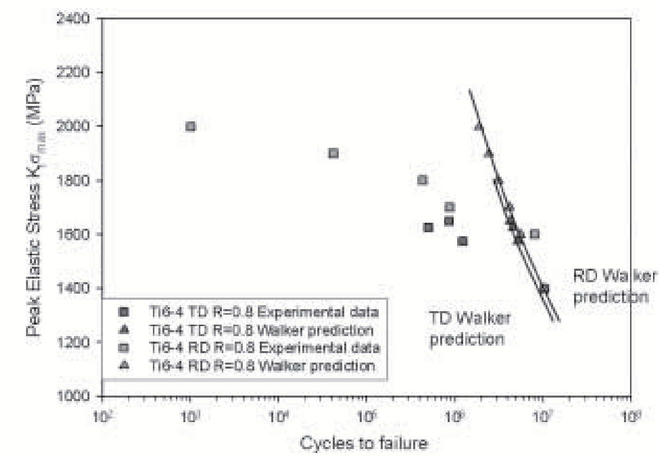

Fig. 11. Walker predictions for RCN at R = 0.8

5. DISCUSSION

The strain control data demonstrate a different response at R=0 between the specimens perpendicular to the rolling direction (90° or TD) and those aligned along the rolling direction (0° or RD). This difference does not occur at R=-1. The difference can be attributed to stress relaxation during the early hysteresis loops for the R=0 experiments. The R=-1 test, however, behave in a near elastic manner and show little relaxation in stress. Replotting the data in terms of stabilised cyclic stress range provides good correlation between RD and TD orientations at both R=0 and -1. Furthermore the two R value families merge at low cyclic lives (<10^5 cycles) but diverge to their respective fatigue limits ($\Delta\sigma$~1000MPa at R=-1 and $\Delta\sigma$~500 MPa at R=0).

Interestingly the K_t= 1.4, RCN specimen display a similar trend to the strain control data when the former are expressed as peak elastic strain range = $K_t\Delta\sigma$ and the latter are plotted in terms of their stabilised cyclic stress range. Titanium alloys display relatively low rates of strain hardening in their stress-strain response. Thus, the stresses in the notched specimen will redistribute throughout the notch section to provide a more uniformly strained volume of material that is similar to the plain specimens. On this basis, the correlation between plain and notched samples in terms of stress range is not unexpected.

Correlations between notches and plain specimens based on stress range, however, are likely to become increasingly inaccurate as the amount of plasticity increases. A far better and generally more effective prediction procedure is the critical strain approach. There are various approaches to critical strain calculations. In this programme, attention was focussed on the Coffin-Manson and Walker relationships.

The Coffin-Manson equation is effective at predicting RCN notch behaviour for the 0° orientation of the textured Ti6-4 material. However, it is relatively inaccurate in its prediction of specimens parallel to the 90° orientation. This is most likely because stress relaxation is more difficult in this orientation. The SEM analysis indicates that both basal and prism slip planes are favourably orientated to support this process in the 0° specimens.

The alternative Walker strain method is able to predict the notch response in both orientations, but does have difficulty in predicting the R = -1 behaviour for the 90° orientation in a similar way to the Coffin-Manson equation. The fact that the Walker method provides a reasonable prediction for R = 0 data is a consequence of the fact that the approach normalises all R values back to R=0 condition. The inaccuracies of the Walker equation are due to the fact that plasticity at the notch root has not been taken into consideration. Allowing for the fall off in the applied peak stress and the associated change in R ratio would improve accuracy.

A major challenge for all life prediction approaches is the high R value response of notch geometries. Figure 11 shows clearly, that the Walker relationship, which is the more effective with regard to mean stress/strain effects, cannot cope with the R=0.8 notch data on the RCN samples. A detailed fractographic analysis demonstrated the reasons. At these ultra high mean stress there is wide spread evidence of quasi-cleavage facet formation and little evidence of striations. An example is shown in figure 12. Quasi cleavage facets indicate high levels of plasticity and particularly plastic strain accumulation with time – also designated cold creep. It is, therefore, argued that the Walker prediction falls down because of the occurrence of additional 'static' modes of crack development.

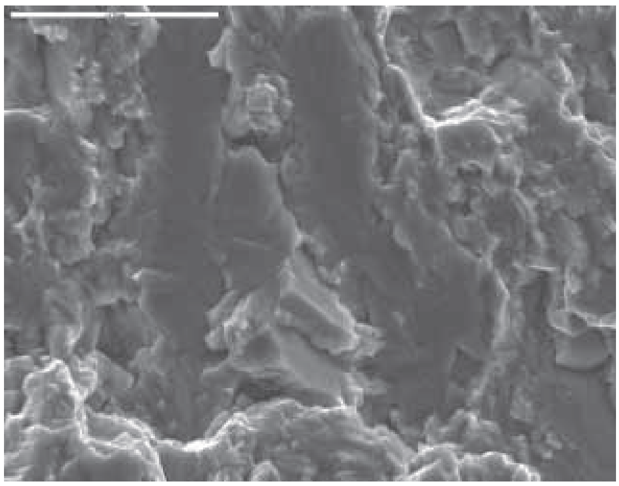

Fig. 12. Quasi cleavage facets in RCN at R=0.8.

6. CONCLUSIONS

- Differences in fatigue life caused by texture are seen in the 0° and 90° specimen orientations under strain control conditions
- The differences in fatigue life of notches caused by crystallographic texture can be predicted from plain specimens provided the specimens have the same orientation
- The Walker strain and Coffin-Manson methods of predicting notch behaviour based on strain control LCF are effective at R=-1 but the Walker is better for R=0.
- The round cylindrical notch, K_t = 1.4 (RCN) can be predicted because of the relatively low K_t of the specimen and large amount of critically stressed material.
- Discrepancies in the prediction of notch behaviour are observed at R=0.8 because of the occurrence of additional failure modes.

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